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# ARES I-X USS Fracture Analysis Loads Spectra Development

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## **Abstract**

This report describes the development of a set of bounding load spectra for the ARES I-X launch vehicle. These load spectra are used in the determination of the critical initial flaw size (CIFS) of the welds in the ARES I-X upper stage simulator (USS).

## **Introduction**

A critical initial flaw size (CIFS) assessment for the welds in the upper stage simulator (USS) of the Ares I-X vehicle was undertaken by the NASA Engineering and Safety Center (NESC). The first step in the CIFS assessment is to define the loading various elements of the USS experience. At the onset of the NESC assessment, a complete design set of prelaunch, liftoff and ascent loads did not exist for the Ares I-X vehicle. It was mutually agreed by the ARES I-X Upper Stage Simulator Project and the NESC team that a consistent set of load spectra would be used by both teams for their otherwise independent life analyses. Therefore, the NESC team worked in partnership with the loads and dynamics engineers in the Ares I-X Vehicle Integration Office, the Constellation Program Ares I Loads Panel, and the structures team of the Ares I-X USS Project office to develop a set of bounding loads spectra expressly for the purpose of application to the fracture mechanics modeling for the CIFS prediction.

The most comprehensive set of design loads existing at the time were the so-called “mini-loads cycle” results for the Ares I vehicle documented in the MSFC Engineering memo EV30-07-001 “Preliminary Design Loads for Ares-I Design Analysis Cycle 2 (ADAC-2)”. The loads provided by this memo resulted from response analyses of pre-launch (pad stay winds), liftoff and ascent flight design environments. Because the design of the Ares I and Ares I-X vehicles did not precisely match, the NESC used the available finite element model geometries of the Ares I-X and Ares I vehicles to interpolate these Ares I loads for the Ares I-X Upper Stage Simulator joint locations.

As the “mini-loads cycle” results were intended for structural strength design purposes, no detailed time history response data were available to perform cycle identification to establish load cycle counts for the CIFS analysis. The team used available environmental data (measured wind speed distributions) or engineering knowledge of the fundamental dynamic response of the launch vehicle to attempt to produce a bounding load spectra for each of the flight regimes discussed below.

Specific flight regimes and pre-launch load conditions considered were: rollout from the VAB to the launch pad, pre-launch pad stay, liftoff, ascent flight, as well as ground handling (crane lifting) and transportation. In this report, each of these loading conditions are discussed and specific loadings are presented.

### **Roll-Out from VAB to Launch Pad**

The Ares I-X Systems Requirements Document [1] allowed for a maximum of five round trips of the AI-X vehicle between the Vehicle Assembly Building (VAB) and the launch pad. The AI-X vehicle will be stacked on a Mobile Launch Platform (MLP) used for Space Shuttle Program and moved by the crawler transporter (CRT). No analytical modeling had been performed by the AI-X project to predict the loads imparted to the AIX specific configuration during this transport, so an assessment was performed by the NESC.

The Ares I-X vehicle was assumed to be supported only at the base, the SRB aft skirt to MLP interface, during transportation from the VAB to the launch complex. At the time of the

analysis, no supplemental support system had been defined by the AI-X Project to reduce vehicle stack response due to winds or rollout.

The NESC commissioned the Loads and Structural Dynamics Branch at the Johnson Space Center (JSC) to perform a forced response analysis using an available NASTRAN model of the Ares I vehicle coupled with a model of the Mobile Launch Platform (MLP) and the Crawler Transporter (CT) available from the Space Shuttle Program. The Ares I model weight was adjusted to include a fully fueled second stage, which most closely approximated the rollout configuration of the Ares I-X vehicle. Two basic forcing function sets were applied to the NASTRAN model as derived from existing measured response data obtained during roll-out testing performed by the Space Shuttle Program: the first set was derived from response data taken during a “partial stack” Shuttle rollout test that consisted of two Shuttle SRBs mounted on a MLP and connected at their ET forward attach points by an ET cross beam that is normally an internal component of the ET intertank; the second forcing function set was derived from response data taken during the rollout of the STS-115 vehicle, a so-called “full stack” set of data. The CT is normally operated up to a speed of 1.0 mph, and forcing functions were available from the Space Shuttle Program at 0.5, 0.6, 0.7, 0.8, 0.9 mph for the “partial stack” data and at 0.8, 0.9, 1.0 mph for the “full stack” data.

The 0.8 mph “partial stack” forcing function applied to the Ares-I model yielded the highest transverse moment response near the base of what would be the USS due to a near-resonant condition with the 2<sup>nd</sup> and 3<sup>rd</sup> bending modes of the vehicle and MLP/CT stack. At a crawler speed of 0.7 or 0.9 mph, the moment response decreased by 50 percent or more. It was decided that both the 0.7 and 0.8 mph responses would be retained to provide sensitivity data should the resulting CIFS analysis prove to be dominated by the rollout environment. The moment responses of both the 0.7 and 0.8 mph speeds were processed through a rainflow cycle identification algorithm to determine the distribution of cycles shown in Table 1 for one simulated 8-hour trip to the pad from the VAB. In the subsequent CIFS analysis, only the 0.8 mph data was used to provide an upper-bound assessment.

**Table 1. Rollout Speed versus Moment Cycles**

<b>Rollout, 8-hours VAB to pad</b>		
<b>% of Design Moment</b>	<b>Number of Cycles</b>	
	<b>0.7 mph</b>	<b>0.8 mph</b>
<b>5%</b>	<b>11160</b>	<b>5256</b>
<b>15%</b>	<b>15048</b>	<b>10584</b>
<b>25%</b>	<b>14688</b>	<b>15768</b>
<b>35%</b>	<b>14256</b>	<b>15840</b>
<b>45%</b>	<b>10296</b>	<b>11592</b>
<b>55%</b>	<b>5904</b>	<b>9936</b>
<b>65%</b>	<b>3240</b>	<b>3744</b>
<b>75%</b>	<b>2232</b>	<b>1440</b>
<b>85%</b>	<b>1800</b>	<b>1224</b>
<b>95%</b>	<b>504</b>	<b>576</b>
<b>100%</b>	<b>72</b>	<b>72</b>
<b>total =</b>	<b>79200</b>	<b>76032</b>

## Pad Stay

The Systems Requirements Document [1] requires the Ares I-X vehicle to be designed for a 50 day stay at the launch pad. The NESC assumed a cumulative 300 day stay based upon the previously mentioned requirement of five round trips to the pad, plus one final stay for the eventual launch. The loads acting on the vehicle during this phase of the life cycle are wind and gravity, thus the bending moment which drives any tensile loading in the vehicle joints is proportional to the wind loading (or the square of the wind speed). The Constellation Program Design Specification for Natural Environments [2] provides the frequency of occurrence distribution for the number of occurrences of peak wind speeds that was used to determine the number of peak wind occurrences in the 300 day period.

At the time of this assessment, both the Ares I and Ares I-X vehicles had been assessed for peak winds corresponding to a 1 percent risk of exceedance for a 10-day pad stay, that is, a peak wind speed of 29.6 meters/second (57.5 knots) at the 18.3 meter reference level for KSC. This was the reference wind speed used to scale the Ares I “mini-loads cycle” pad stay loads to develop the pad winds spectra provided in Table 2. However, Constellation Program requirements also impose a 38.3 meter/second design wind that must be included as at least one occurrence in any fatigue life assessments. The bending moment from the design peak wind speed of 29.6 meters/second was thus scaled by square of the velocity ratio and a single cycle was added for this condition in the CIFS analysis. The wind loads were all applied as fully reversed cycles in the CIFS analysis, as yet a further upper-bound assumption.

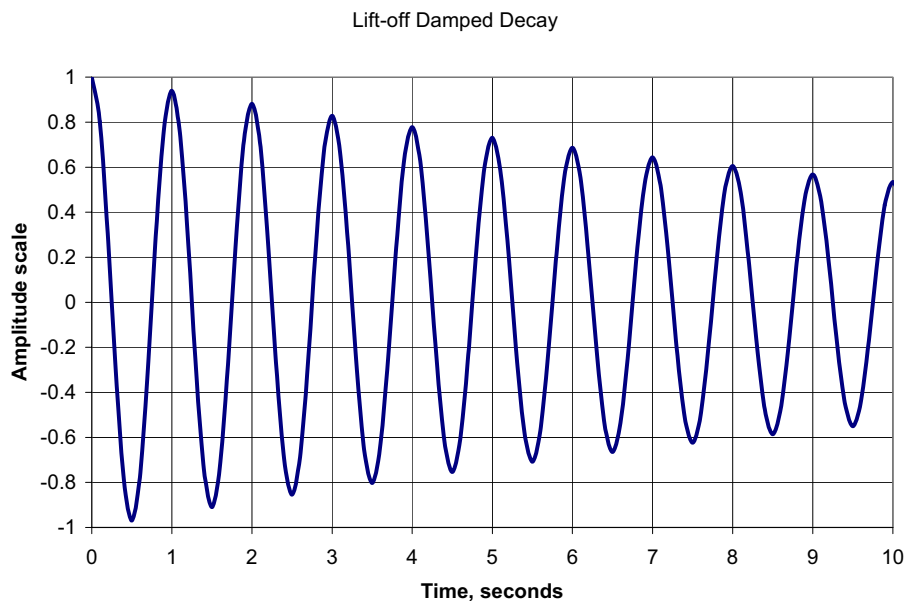
**Table 2. Wind Loading Distribution**

<b>Prelaunch wind</b>			
<b>% of Design Moment</b>	<b>Number of Cycles</b>		
	<b>50-day pad stay</b>	<b>6x50-day pad stay</b>	<b>300-day pad stay</b>
<b>5%</b>	<b>118474</b>	<b>710,844</b>	<b>710,843</b>
<b>15%</b>	<b>23729</b>	<b>142,374</b>	<b>142,371</b>
<b>25%</b>	<b>1383</b>	<b>8,298</b>	<b>8,299</b>
<b>35%</b>	<b>260</b>	<b>1,560</b>	<b>1,562</b>
<b>45%</b>	<b>40</b>	<b>240</b>	<b>242</b>
<b>55%</b>	<b>15</b>	<b>90</b>	<b>89</b>
<b>65%</b>	<b>3</b>	<b>18</b>	<b>17</b>
<b>75%</b>	<b>0</b>	<b>0</b>	<b>8</b>
<b>85%</b>	<b>0</b>	<b>0</b>	<b>3</b>
<b>95%</b>	<b>0</b>	<b>0</b>	<b>1</b>
<b>100%</b>	<b>1</b>	<b>1</b>	<b>1</b>
<b>Total =</b>		<b>863,425</b>	<b>863,437</b>



## Liftoff

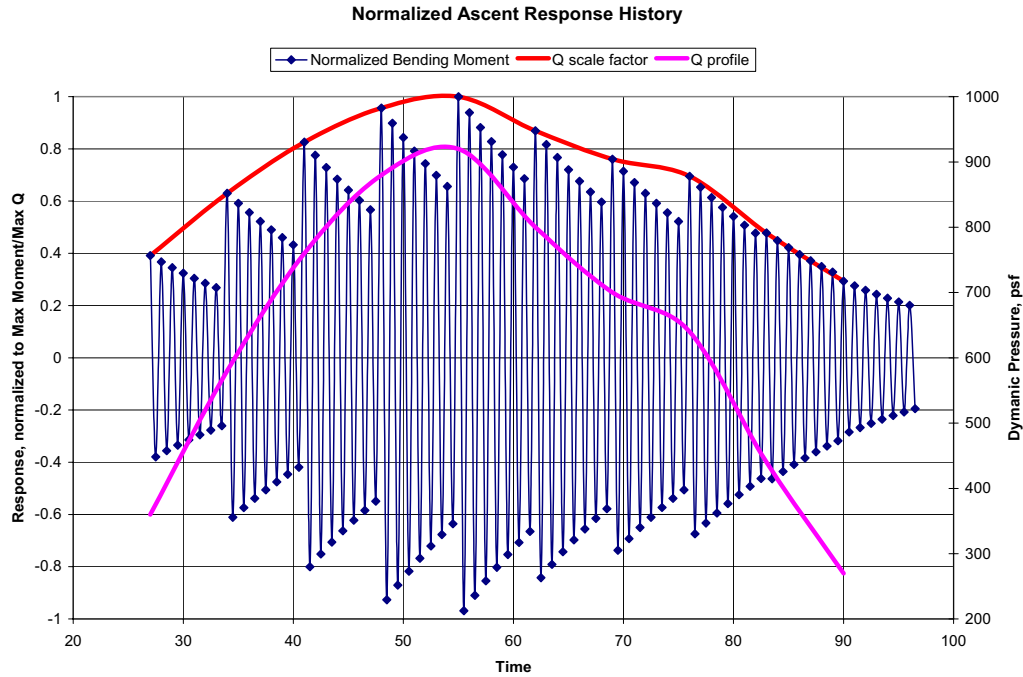
The liftoff event was assumed to occur over 10-second duration and was assumed to excite the vehicle in free vibration in its first mode of 1 Hz. The cyclic loads experienced during this phase of the life cycle were estimated by approximating the vehicle response as the initial peak load of the liftoff design moment followed by a sinusoidal decay at 1 Hz and 1 percent damping, as shown in Figure 1.



**Figure 1. Liftoff Damped Decay**

## Ascent

The duration of the powered ascent phase of the Ares I-X flight is approximately 120 seconds, as determined by burn-out of the Space Shuttle SRB used as the first stage. However, for this analysis a 70 second period of significant dynamic pressure ( $Q > \sim 350$  psf) was determined from examination of a typical Ares I planned ascent trajectory. The maximum ascent bending moment from the Ares I mini-loads cycle was assumed to occur at the time of maximum dynamic pressure. A series of ten equally timed ascent loads events was assumed to occur in this 70 second period as an approximation to a series of gust load events. The bending moment at each event time was scaled in proportion to the ratio of  $Q$  at that time to  $Q_{\max}$ . The bending moment for each of the 10 “gust” events was assumed to decay in the seven second interval as a free vibration at 1 Hz with a 1 percent damping rate, as shown in Figure 2.



**Figure 2. Normalized Ascent Response History**

## Ground handling and Transportation Loads

Each segment of the Ares I-X hardware is manufactured separately and is lifted and transported locally several times during assembly. The team assumed that the lifting event consisted of a single 1.5 proof load, 11 multi-segment lifts, and 42 single segment lifts. The transportation event consists of peak loads estimated for shipboard travel. The number of cycles and decay of the shipboard loads were derived from the characteristics of a 50-day pad stay. This assumption was made in the absence of actual transportation data and is believed to be conservative.

## Concluding Remarks

A bounding set of load spectra were developed for the Ares I-X launch vehicle. These loads were developed for the purpose determining the CIFS of the Ares I-X USS welds. Various flight regimes and pre-launch load conditions were considered. These are roll out from the vehicle assembly building to the launch pad, pre-launch pad stay, lift-off, ascent, ground handling (crane lifting), and transportation. For each of these conditions available environmental data, engineering knowledge, and previous historical data about the load regimes were used in developing the load spectra. The developed bounding load spectra were used by the NESC team in determining the CIFS of the welds in the USS.

**References:**

1. System Requirements Document, CxP zzzz, 2007.
2. *Constellation Program Design Specification for Natural Environments*, CxP 70023, 2007.

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